Parallel-in-space-and-time scheme for implicitly coupled electromechanical and electromagnetic transients simulation

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Overview

- Combined Electromechanical and Electromagnetic Transients Simulation (TSEMT)
- Implicitly coupled solution approach for TSEMT
- Parallel-in-space-and-time partitioning scheme
- Parallel performance results

Power system dynamics simulation

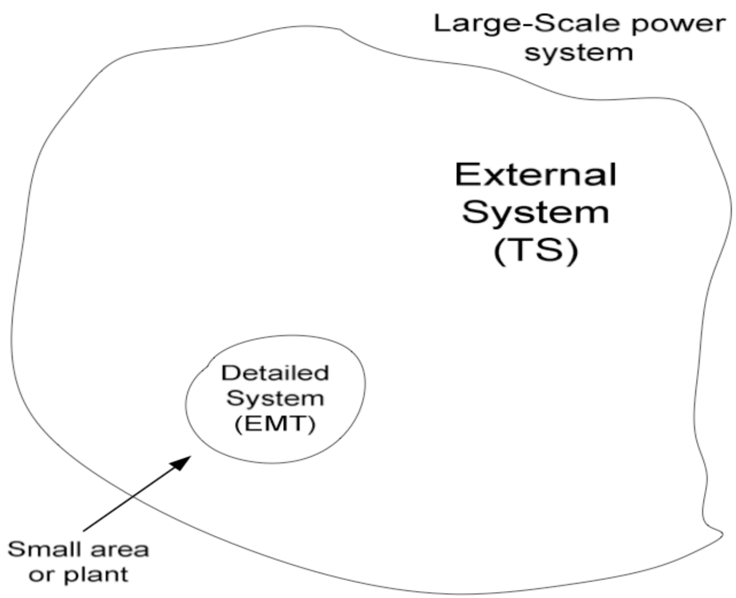
Transient stability simulators (TS)

- Balanced network (per-phase analysis)
- Nearly constant frequency (phasors)
- Time-step in milliseconds
- Less computationally intensive (in comparison to EMT)
- Assessing system stability of large-scale power grids

Electromagnetic transient simulators (EMT)

- Unbalanced three-phase network
- Instantaneous signals
- Time-step in microseconds
- More computationally intensive
- Studying the dynamics of fast-switching power electronic equipment.

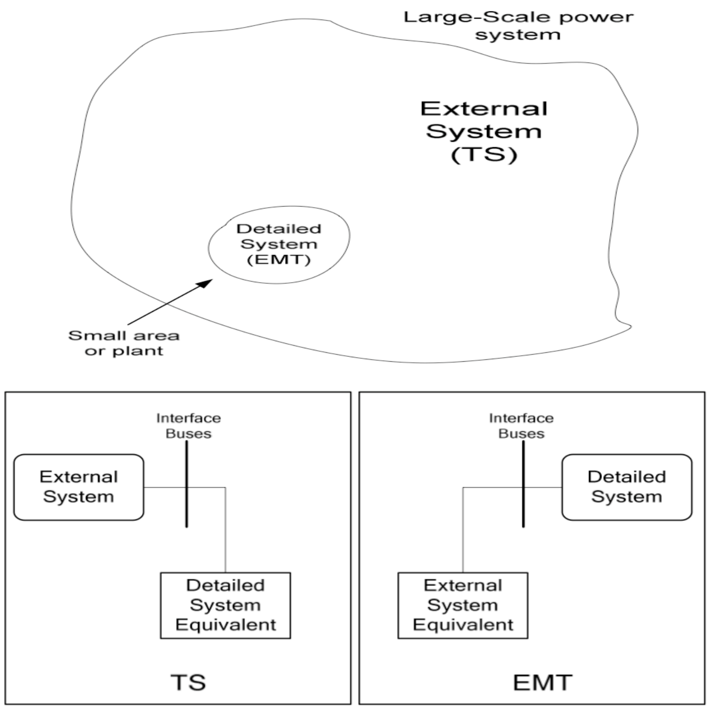
Combined TS-EMT



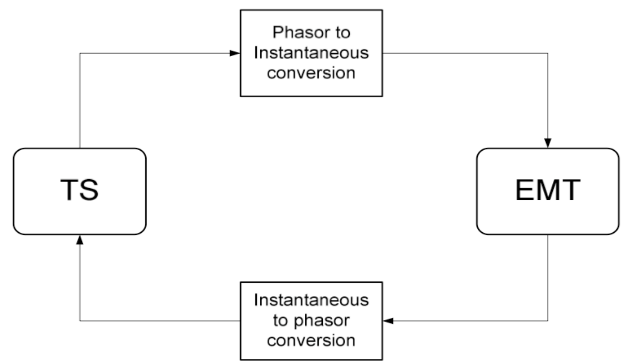
Combined TS-EMT ("Hybrid simulation")

- First proposed by Hefernan et. al. for HVAC-HVDC analysis.
- Further motivation from modeling of FACTS devices.
- 'Interface' separate TS and EMT programs.

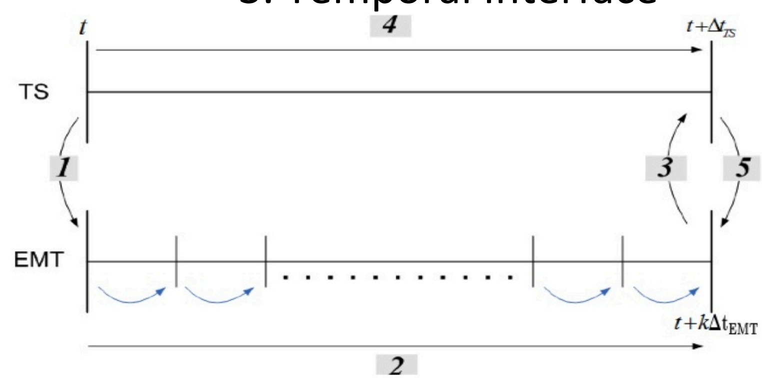
1. Spatial Interface



2. Waveform Interface

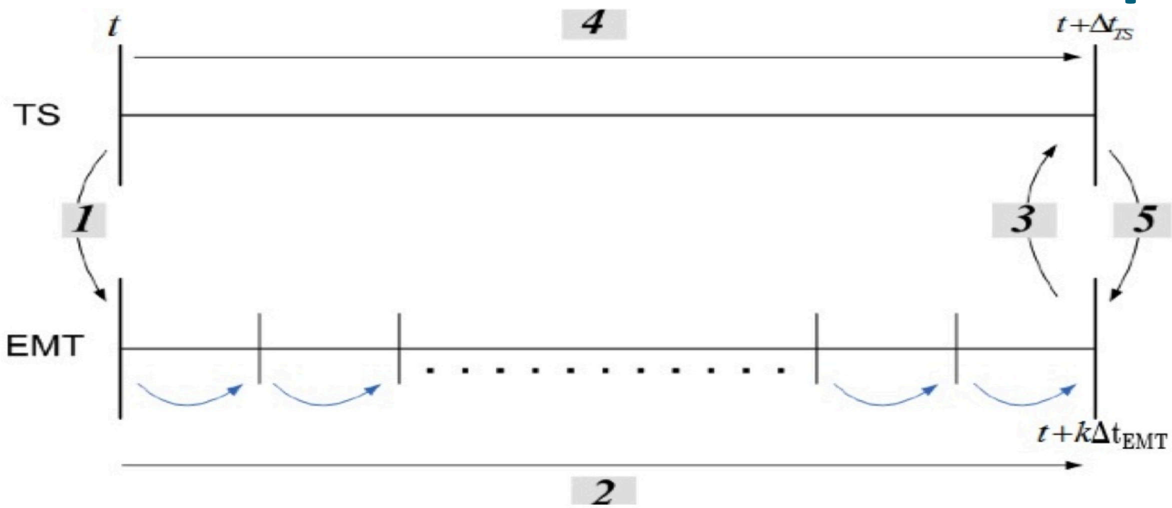


3. Temporal Interface



IEEE Task Force on Interfacing Techniques for Simulation Tools, "Interfacing techniques for transient stability and electromagnetic transients program," IEEE Transactions on Power Systems, vol. 8, pp. 2385–2395, 2009.

Hybrid simulation serial interaction protocol



① TS passes external system equivalent at time t.
② EMT commences and runs till next TS time step one EMT step at a time.
③ EMT passes the detailed system equivalent to TS.
④ TS computes the solution for the next time step.
⑤ TS passes the external system equivalent to EMT.

Note* : The external system equivalent passed to EMT is constant.

Note* : No iterations done between TS and EMT.

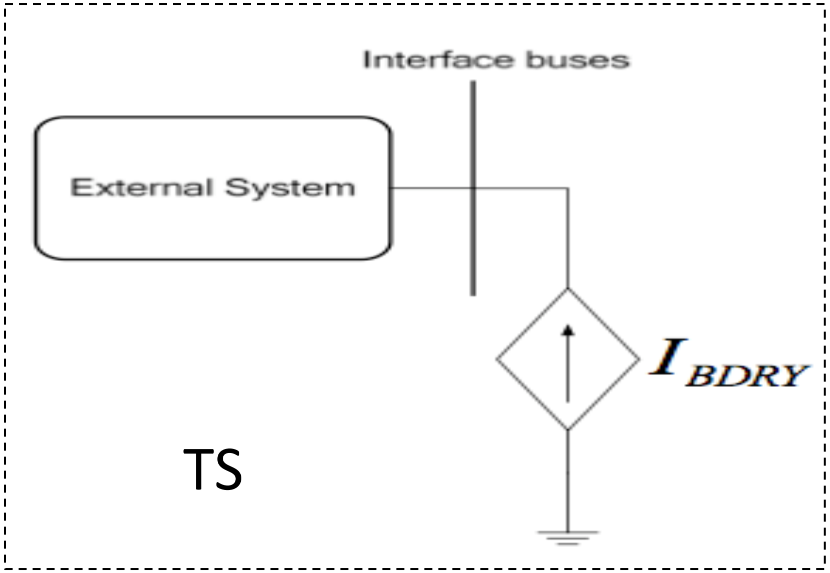
Can possibly have large interface errors leading to divergence when system states are changing rapidly [1]

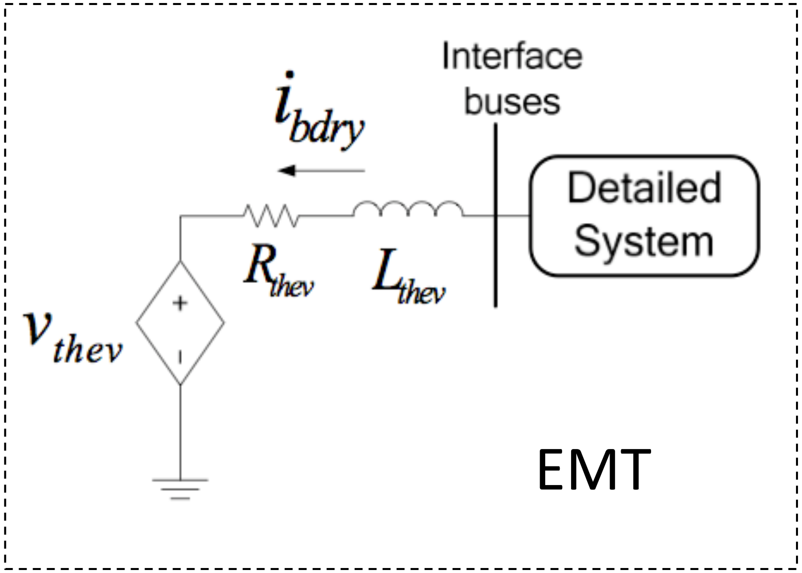
[1] S. Abhyankar and A. Flueck, "An implicitly-coupled solution approach for combined electromechanical and electromagnetic transients simulation," in *Proceedings of the IEEE PES General Meeting*. IEEE, 2012.

Implicitly coupled solution approach for TSEMT

- Can couple at the solution level rather than at application level, in other words **Solve TS and EMT equations simultaneously**.
- Solve TS and coupled-in-time EMT equations in a single large system at each TS time step.
- External equivalents and waveform interface form implicit coupling.
- More details? www.mcs.anl.gov/~abhyshr/research
  - S. Abhyankar and A. Flueck, "An implicitly-coupled solution approach for combined electromechanical and electromagnetic transients simulation," in *Proceedings of the IEEE PES General Meeting*. IEEE, 2012.
  - S. Abhyankar, "Development of an implicitly coupled electromechanical and electromagnetic transients simulator for power systems," Ph.D. dissertation, Illinois Institute of Technology, 2011.

TSEMT interfacing details





- Dependent phasor current source computed via fourier analysis

$$I_{BDRY,D}(t+\Delta t_{TS}) = \frac{2}{T}\int_{\tau=t}^{t+\Delta t_{TS}} i_{bdry}(\tau)\sin(\omega\tau)d\tau$$

$$I_{BDRY,Q}(t+\Delta t_{TS}) = \frac{2}{T}\int_{\tau=t}^{t+\Delta t_{TS}} i_{bdry}(\tau)\cos(\omega\tau)d\tau$$

- Modified TS network current balance equation

$$YV = I_{gen} - I_{load} + I_{BDRY}$$

- Uses fundamental frequency Thevenin equivalent of the external system

$$V_{bdry} = \overbrace{Z_{bdry,int}Z_{int,int}^{-1}V_{int}}^{\text{Thevenin voltage source}} - \overbrace{\left(Z_{bdry,int}Z_{int,int}^{-1}Z_{int,bdry} - Z_{bdry,bdry}\right)}^{\text{Thevenin equivalent impedance}} I_{bdry}$$

- Thevenin impedance kept constant, only Thevenin voltage updated at each TS time step.
- Additional equation for EMT

$$L_{thev}\frac{di_{bdry}}{dt} = v_{thev} - R_{thev}i_{bdry} - v_{bdry}$$

Implicitly coupled solution approach

- Equations for each TS and EMT time step

$$\frac{dX_{TS}}{dt} = F(X_{TS}, V_{TS})$$

$$0 = G(X_{TS}, V_{TS}, I_{BDRY})$$

$$\frac{dx_{EMT}}{dt} = f_1(x_{EMT}, i_{bdry})$$

$$\frac{di_{bdry}}{dt} = f_2(x_{EMT}, i_{bdry}, v_{thev})$$

- **Approach : Solve TS and coupled-in-time EMT equations simultaneously at each TS time step in a single large system.**
- Equations solved using Newton's method.
- We use a state-space model for EMT (hence the differential equations), can also use NIS.

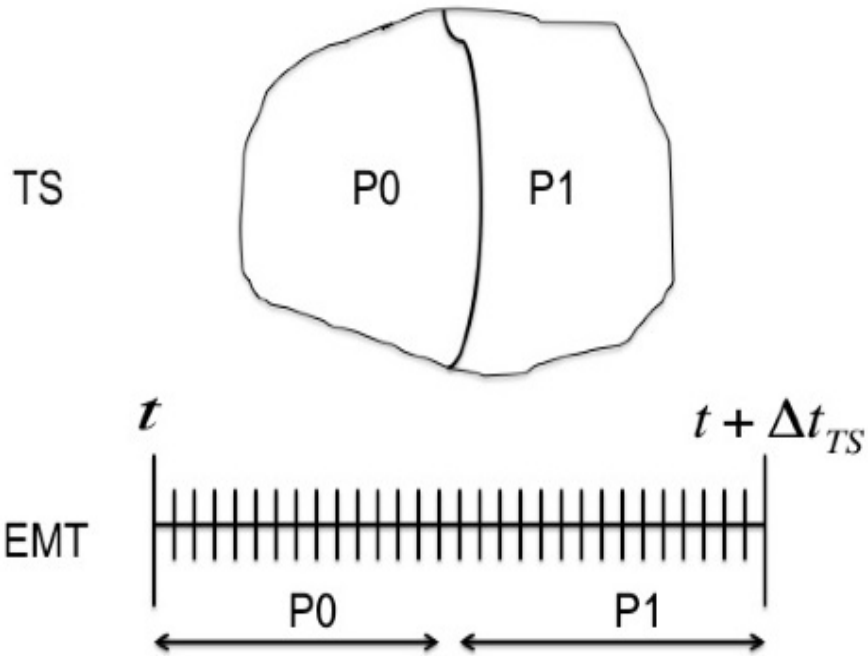
$$\left\{\begin{aligned}
&X_{TS}(t_{N+1}) - X_{TS}(t_N) - \\
&\quad \frac{\Delta t_{TS}}{2}(F(t_{N+1}) + F(t_N)) = 0 && (6)\\
&\quad G(t_{N+1}) = 0 && (7)\\
&x_{EMT}(t_{n+1}) - x_{EMT}(t_n) - \\
&\quad \frac{\Delta t_{EMT}}{2}(f_1(t_{n+1}) + f_1(t_n)) = 0 && (8)\\
&i_{bdry}(t_{n+1}) - i_{bdry}(t_n) - \\
&\quad \frac{\Delta t_{EMT}}{2}(f_2(t_{n+1}) + f_2(t_n)) = 0 && (9)\\
&x_{EMT}(t_{n+2}) - x_{EMT}(t_{n+1}) - \\
&\quad \frac{\Delta t_{EMT}}{2}(f_1(t_{n+2}) + f_1(t_{n+1})) = 0 && (10)\\
&i_{bdry}(t_{n+2}) - i_{bdry}(t_{n+1}) - \\
&\quad \frac{\Delta t_{EMT}}{2}(f_2(t_{n+2}) + f_2(t_{n+1})) = 0 && (11)\\
&\quad \vdots\\
&\quad \vdots\\
&x_{EMT}(t_{n+k}) - x_{EMT}(t_{n+k-1}) - \\
&\quad \frac{\Delta t_{EMT}}{2}(f_1(t_{n+k}) + f_1(t_{n+k-1})) = 0 && (12)\\
&i_{bdry}(t_{n+k}) - i_{bdry}(t_{n+k-1}) - \\
&\quad \frac{\Delta t_{EMT}}{2}(f_2(t_{n+k}) + f_2(t_{n+k-1})) = 0 && (13)
\end{aligned}\right.$$

Parallel implementation

- We use a spatial decomposition (i.e. parallel-in-space) for TS equations and temporal decomposition (i.e. parallel-in-time) for EMT equations.
  - TS system larger than EMT system.
  - Solving coupled-in-time EMT equations.
  - Generators and loads are incident at nodes.
  - Minimize load balancing.

Parallel-space-time partitioning

Partition TS in space



Partition EMT in time

Equations assigned to each processor

TS

$$
\begin{aligned}
\frac{dX_{TS}^{p}}{dt} &= F(X_{TS}^{p}, V_{TS}^{p}) \\
0 &= G(X_{TS}^{p}, V_{TS}^{p}, V_{TS}^{c}, I_{BDRY})
\end{aligned}
$$

EMT

$$
x_{EMT}(t_{m+1}) - x_{EMT}(t_m) - \frac{\Delta t_{EMT}}{2}(f_1(t_{m+1}) + f_1(t_m)) = 0 \quad (15)
$$

$$
i_{bdry}(t_{m+1}) - i_{bdry}(t_m) - \frac{\Delta t_{EMT}}{2}(f_2(t_{m+1}) + f_2(t_m)) = 0 \quad (16)
$$

$$
x_{EMT}(t_{m+2}) - x_{EMT}(t_{m+1}) - \frac{\Delta t_{EMT}}{2}(f_1(t_{m+2}) + f_1(t_{m+1})) = 0 \quad (17)
$$

$$
i_{bdry}(t_{m+2}) - i_{bdry}(t_{m+1}) - \frac{\Delta t_{EMT}}{2}(f_2(t_{m+2}) + f_2(t_{m+1})) = 0 \quad (18)
$$

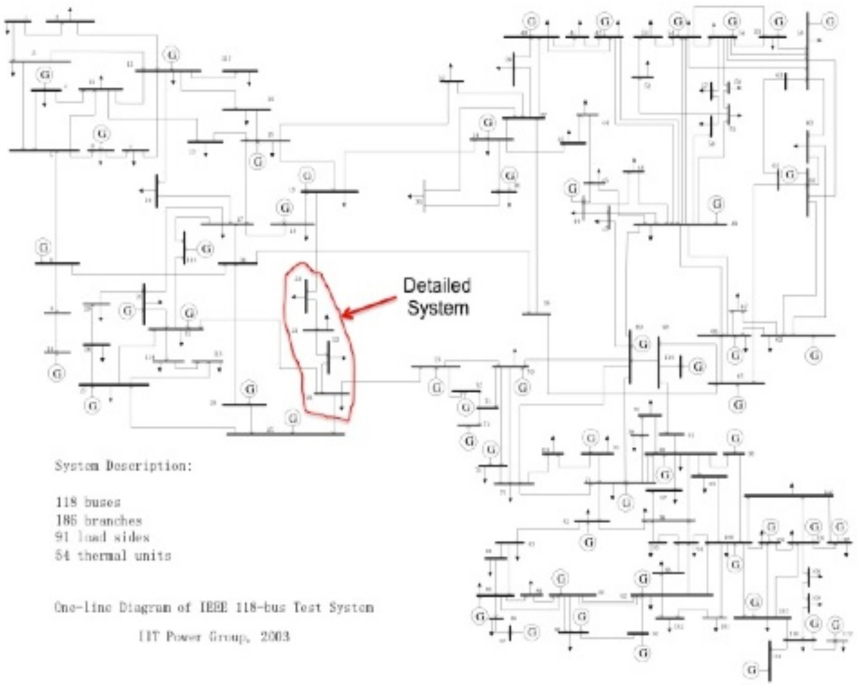
$$
\vdots
$$

$$
\vdots
$$

$$
x_{EMT}(t_{m+p}) - x_{EMT}(t_{m+p-1}) - \frac{\Delta t_{EMT}}{2}(f_1(t_{m+p}) + f_1(t_{m+p-1})) = 0 \quad (19)
$$

$$
i_{bdry}(t_{m+p}) - i_{bdry}(t_{m+p-1}) - \frac{\Delta t_{EMT}}{2}(f_2(t_{m+p}) + f_2(t_{m+p-1})) = 0 \quad (20)
$$

Test case details



- IEEE 118 bus system
- EMT part is a radial portion consisting of 4 buses, 3 transmission lines, load at each bus.
- Loads modeled as constant impedance loads.
- Generators are 6th order models with exciter.

Simulation details

- TS time step = 0.01667 seconds
- EMT time step = 0.00016667 seconds
- Three-phase fault in EMT system cleared in 0.1 seconds.
- Simulation time-length = 1 second.
- Used ParMetis for partitioning the
- TS system

Machine and code details

- AMD Interlagos NUMA machine
- 4 sockets, 16 cores/socket
- AMD Opteron 6274 processors
- @2.2 GHz
- Code written in C using PETSc's numerical solvers.
- Uses MPI for inter-processor communication (used by PETSc's solvers)
- GNU gcc compiler with –O3 optimization

Numerical solution schemes

Solution using Newton's method with different parallel linear solution strategies

1. Parallel LU solver MUMPS
   - Parallel LU factorization based on multifrontal approach.
   - P. R. Amestoy, I. S. Duff, J.-Y. L'Excellent, and J. Koster "A fully asynchronous multifrontal solver using distributed dynamic scheduling," *SIAM Journal on Matrix Analysis and Applications,* vol. 23, no. 1, pp. 15–41, 2001
2. GMRES with Block-Jacobi preconditioner
   - GMRES: Iterative Krylov-subspace based solver for unsymmetrical systems.
   - Convergence depends on the eigen spectrum of the linear operator.
   - Generally requires a good preconditioner.
   - We use a Block-Jacobi preconditioner

$$\begin{array}{c} 0 \\ 1 \end{array} \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \qquad\qquad \begin{array}{c} 0 \\ 1 \end{array} \begin{bmatrix} J_1^{-1} & \\ & J_4^{-1} \end{bmatrix}$$

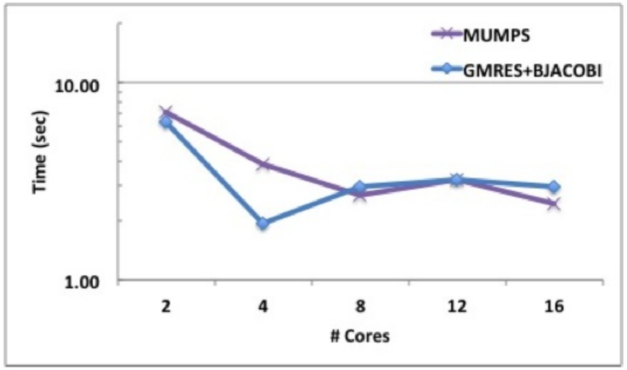
Jacobian on 2 cores — Block-Jacobi preconditioner

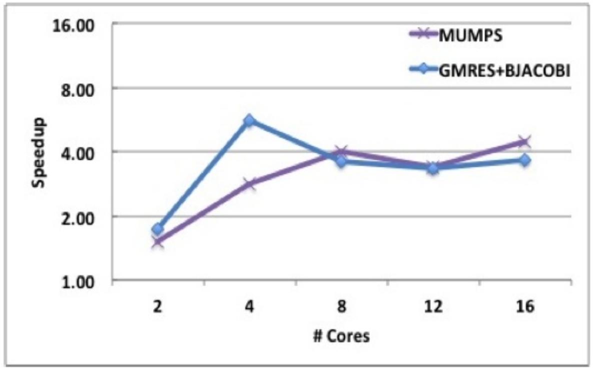
No communication for building or applying the preconditioner
Can choose the factorization, reordering independently on each block.
We use LU with Quotient Minimum Degree ordering on each block.

Wall-clock time

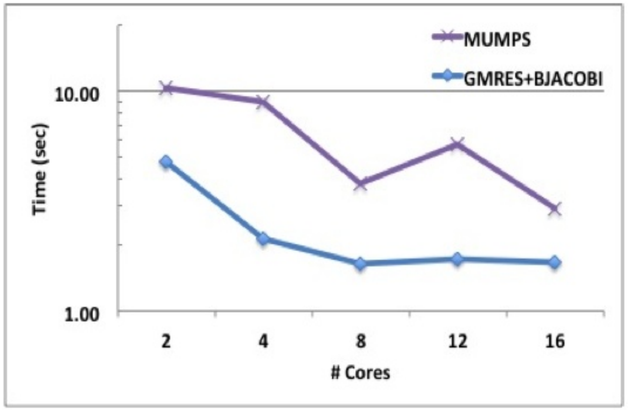
Speedup

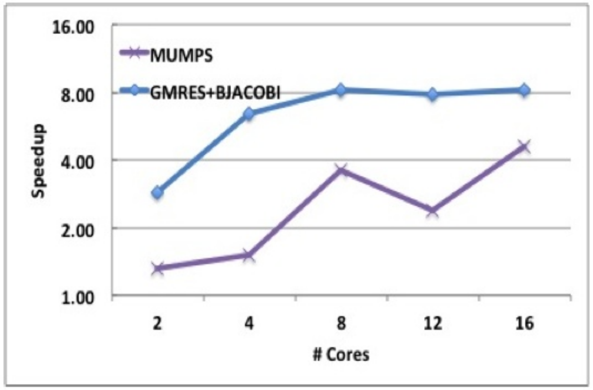
118 bus



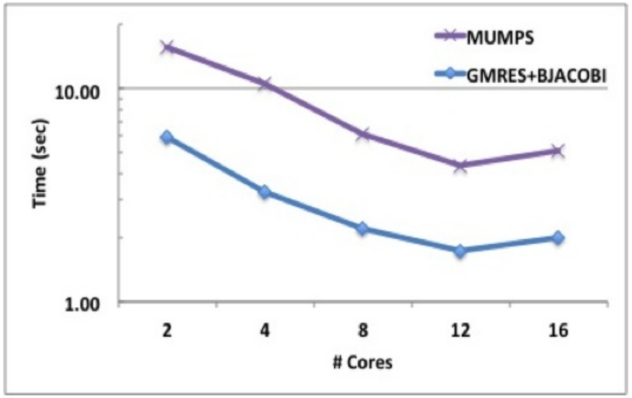


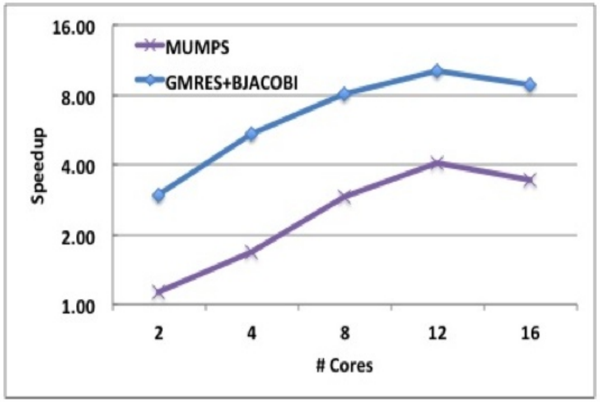
6 X 118
708 bus





10 X 118
1080 bus





Software Framework: PETSc

Portable **E**xtensible **T**oolkit for **S**cientific **C**omputation

- "Open-source" numerical library for large-scale parallel computation.
- Portability
  - Tightly/loosely coupled architectures
  - Unix, Linux, MacOS, Windows
  - 32/64 bit, real/complex, single/double/quad precision
  - C, C++, Fortran, Python, MATLAB.
  - GPGPUs and support for threads
- Extensibility
  - ParMetis, SuperLU, SuperLU_Dist, MUMPS, HYPRE,UMFPACK, Sundials, Elemental, Scalapack, UMFPack, …
- Toolkit
  - Sequential and Parallel vectors.
  - Sequential and Parallel matrices.
  - Iterative linear solvers and preconditioners.
  - Parallel nonlinear solvers.
  - Parallel timestepping (ODE and DAE) solvers.
- Runtime options!! Great for fast experimentation.

Summary and Future Work

- Presented a parallel-in-space-and-time decomposition strategy for solving implicitly-coupled electromechanical and electromagnetic transients simulation.
- Analyzed the parallel performance with two linear solvers
  - Iterative solver GMRES with Block-Jacobi preconditioner
  - Parallel LU factorization using MUMPS.
- Preconditioned GMRES found to be more scalable than MUMPS for different test cases.
- Future work
  - Need better EMT equipment models especially fast-switching devices, algorithm to handle discontinuities within TS time step.
  - Investigate other network equivalents for TS and EMT.